A FIELD STUDY OF PARTICULATE EMISSIONS FOR MAJOR ROADWAYS IN THE PHOENIX AIRSHED

Final Report 495

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16. Abstract

This report describes field experiments conducted to determine particulate emission amounts for PM_{10} along freeways in the greater Phoenix area. A field site at Mile 47 on Loop 101 near the Chaparral Road exit was chosen for experiments conducted in Feb-Mar 2001 and Feb-Mar 2002. Three mobile laboratories with instruments for measuring and sampling aerosol particles and measuring meteorological parameters were deployed, one on each side 3 m from the roadway and, in Mar 2002, one 100 m to the west of the roadway. A 10 m tower was also used to determine the vertical profiles of wind velocity and direction, and aerosol concentration. Soil dust particles dominate the freeway aerosol , but it also has significant concentrations of black carbon (soot) and iron oxide or other metal Many of the iron-rich particles are hypothesized to result from engine wear, although other sources of iron-rich particles are known in the Phoenix area. The measured emission factor for this experiment was 0.1 grams per vehicle kilometer traveled, a value that is similar to an emission factor calculated for roads in southern California through modeling by other investigators. However, emission factors such as this are not constants and can be expected to vary with changes in conditions such as vehicle fleet composition and loading of dust on the road surface. Vertical profiles of wind and aerosol are in disagreement with the assumptions made in current line source models; if the measured vertical profiles are used in the emission factor calculation, the emission factor is reduced to 0.06 grams per vehicle kilometer traveled. Both values are similar to MOBILE6 model results by the Arizona Department of Environmental Quality for freeways in Maricopa County. Low wind conditions are very common in the Phoenix area. When wind speeds are below a critical value (4-5 mph), PM_{10} aerosol concentrations build to high values. This is because the turbulence from passing vehicles becomes more pronounced than the normal surface winds; under such conditions the aerosols are trapped in an essentially narrow, elongate plume above the freeways. When the low wind conditions break down, wind speed increases, and the plume of aerosol is dispersed down wind. The ratio of $PM_{2.5}$ to PM_{10} is dependent on wind speed as well and can be very high when the wind speed is below the critical value. The evidence suggests that new dust is constantly being loaded onto the freeway surface so that the freeway is a perpetual source of PM_{10}. The observations about high PM concentrations during frequent periods of low wind speed have broader implications for urban freeways. The control of noise by building urban freeways below grade, with high sound walls or both can artificially create low wind conditions for longer periods than naturally occur; the consequences of artificially created wind stagnation with regard to PM levels is as yet undetermined.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
AREA				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: Volumes greater than 1000L shall be shown in m^3.				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000lb)	0.907	megagrams (or "metric ton")	mg (or "t")
TEMPERATURE (exact)				
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celsius temperature	°C
ILLUMINATION				
fc	foot candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m²	cd/m²
FORCE AND PRESSURE OR STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm^2	Square millimeters	0.0016	square inches	in^2
m^2	Square meters	10.764	square feet	ft^2
m^2	Square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	Square kilometers	0.386	square miles	mi^2
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	Cubic meters	35.315	cubic feet	ft^3
m^3	Cubic meters	1.308	cubic yards	yd^3
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (or "metric ton")	1.102	short tons (2000lb)	T
TEMPERATURE (exact)				
°C	Celsius temperature	1.8C + 32	Fahrenheit temperature	°F
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
cd/m²	candela/m²	0.2919	foot-Lamberts	fl
FORCE AND PRESSURE OR STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380

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I. INTRODUCTION

PROJECT BACKGROUND AND PURPOSE

The determination of of emission factors for suspended dust (crustal material) from the passage of vehicles in major roadways is essential in the planning of freeway and highway systems. This is especially true in urban areas like Phoenix that are in non-compliance with the National Ambient Air Quality Standard for $PM_{10,}$ which governs the allowable mass of particles 10 micrometers (μm) and smaller in diameter per unit volume of air. Unlike emission factors for exhaust particles, which can be measured directly from the point of origin (e.g., tailpipes for automobiles), dust entrained from the road surface by turbulence cannot be easily distinguished from similar crustal material from other sources (agriculture, sand and gravel mining, construction, etc.). In practice, empirical mathematical expressions use more easily measured parameters to estimate dust emission factors. For paved roads the key parameter is "silt loading." There are serious concerns about the validity of this method, and therefore the emission factors so derived have uncertain validity. However, in the past, direct field measurement of particulate emission factors has proven to be difficult because it requires an experimental design that can separate the background aerosol from the emissions of a particular roadway. Below is a discussion of the results of experiments that were conducted on urban freeways in the Phoenix airshed that have allowed direct measurement of PM_{10} emission factors for the vehicle fleet on Loop 101.

Another major objective of this work was to understand the particulate loading along a freeway during the wind conditions that typify high particulate pollution periods in complex terrain areas like Phoenix. The worst PM_{10} conditions occur when wind speed is very low, below 2.5 meters per second (m/s) or 5 miles per hour (mph), and during brief periods of high wind (e.g., summer monsoon dust storms). All of the current models of particulates from roadways are not applicable to low wind speed conditions, something that occurs at least twice on a typical day in Phoenix or Tucson. Presented here are resultof experiments tracking the buildup of PM_{10} concentrations during these periods of low wind speed, and aspects of the dispersion of aerosols downwind from major roadways when the low wind speed conditions end.

There is a serious disparity between receptor-model and emission-inventory estimates of the contribution that combustion sources make to fine particulates. For the Phoenix area, receptor models estimate that 70% of primary fine particulates come from mobile source combustion. In contrast, emission inventories estimate that 18% come from this source. Part of the disparity is possibly due to overestimates of re-entrained dust. More of the disparity may stem from a lack of knowledge of the composition of re-entrained dust, which may consist of aggregates of soil particles with carbonaceous material rather than just soil particles alone. Along with the challenge of separating freeway particulates from background particulates, this study has employed methods that allow particles re-entrained off the road surface to be distinguished from vehicle exhaust particles such as soot and that allow determination of the extent of aggregation of soot and soil dust.

Although roadway-derived particulates ultimately add to the ambient urban air pollution, the most severe potential impact of re-entrained dust on human health will be in

residential areas and schools close to major roadways with significant heavy truck traffic. Little is known about the decay of downwind concentrations of roadway dust in complex terrain areas of the southwest like Phoenix. This is also discussed below.

The size distribution of roadway-derived aerosols is, while secondary to PM_{10} concentrations for strictly regulatory purposes, an important issue with regard to human health. Largely anecdotal evidence in the literature suggests that soil dust particles are reduced in size when driven over by vehicles. If the average particle size of re-entrained dust is smaller than that of soil dust from other sources, then the potential for respiration deep into human lungs is enhanced; also, the contribution to regional PM_{10} is effectively greater because of the reduced average settling velocity.

OBJECTIVES OF STUDY

- To determine PM_{10} emission factors for total vehicle-related particulates on major roadways in the Phoenix urban airshed.
- To determine PM_{10} emission factors for re-entrainment of mineral dust particles from major roadways including data by vehicle type and speed so as to assess the impact on the ambient urban aerosol.
- To determine the downwind contributions of roadway particles to PM_{10} at distances of up to 100 m, so as to assess the local impact of freeways on adjacent residential areas.
- To determine whether re-entrained mineral dust is aggregated with significant amounts of carbonaceous material.
- To determine the size distribution of re-entrained dust and, if reduced from other ambient dust, the mechanism responsible.

CURRENT KNOWLEDGE OF PM_{10} EMISSION FACTORS FROM PAVED ROADS

The equation that the U.S. Environmental Protection Agency (EPA) recommends for determining emission factors for dust emissions from paved roads is AP-42 (USEPA 1984, 1991). AP-42 came from work mostly in the Midwest and involves taking dust samples from the road surface by sweeping a known area, then measuring the fraction of material that is "silt" (particles smaller than 75 μm in diameter). A variety of studies have shown the AP-42 relationship to be of little value in Western urban areas (e.g., Fitz; 1998; Venkatram and Fitz, 1998); it is doubtful the empirical relationship works anywhere other than where it was first derived. AP-42 may not provide accurate emission factors of roadway dust in Arizona or other Western states.

The current state of knowledge about PM_{10} emissions from paved roads, including free-ways, is well summarized by Venkatram et al (1999). Their modeling results, partly based on experiments conducted in Riverside, California, estimate that freeway PM_{10} emission factors are on the order of 0.2 grams per vehicle kilometer traveled (g VKT^{-1}), with an uncertainly on the order of a factor of two. Their field experiments with upwind-downwind measurements were not entirely satisfactory, probably because the complica-tions involved in continually changing wind conditions can only be overcome with real-

time measurements. They did, however, add further evidence that the AP-42 emission factors are unsatisfactory.

WIND FIELDS IN COMPLEX TERRAIN

Phoenix, Tucson, and most other urban areas of the West lie in areas with hills, mountains, and valleys). While occasionally the surface winds are driven by pressure gradients due to passing frontal systems (e.g., synoptic flow), more typically the surface flows are driven by the diurnal heating and cooling of uneven terrain, resulting in slope flows and valley flows. (Stull, 1988; Fernando et al., 2001). During the day, surface winds flow either up-slope or up-valley (depending on the dominant topography); with sunset surface cooling begins and flows are either down-slope or down-valley. These thermally driven, terrain-controlled surface winds are low in speed compared to winds in cities with flat terrain. In addition, the transition periods between cooling and heating in the morning and between heating and cooling in the evening result in times when the wind speed drops to near zero. This stagnation during thermal transition is critical to the behavior of particulate concentrations along freeways.

In general, for Phoenix and similar Western urban areas, the typical days on which the complex terrain flows dominate are the days on which the concentrations of pollutants tend to be the highest. Infrequent dust storms cause high particulate levels ; at those times, particulate emissions from paved roadways are of little consequence: the only possible impact that a dust storm could have on the roadway is to occasionally load dust on its surface.Since it is clear from these results that reloading of the roadway surfaces is continually occurring, most likely from track-on of construction dust, the infrequent loading by dust storms is probably not very important on an annual basis.

LIMITATIONS OF THE STUDY

Emission factors for re-entrained dust (from road surface to the air) depend on a number of parameters that are difficult to control in any field experiment. The study team was fortunate to encounter suitable experimental conditions at one of the field sites (Loop 101 near Chaparral Road on the Salt River Pima- Maricopa Indian Community, near the border with Scottsdale), but two other sites on I-10 that would have sampled a different fleet composition were problematic for a variety of reasons, including obstacles that had severe impact on surface wind speeds and directions, and also repeated vandalism. The only suitable sites for unobstructed experiments along I-10 are south of the Phoenix metro area, beyond the study area of this project.

One key parameter in the experiments is the fleet composition passing a site. It was measured in this study by videotaping traffic, since the turbulent wake of a vehicle depends upon its size, shape, and speed. The fleet on Loop 101 has far fewer large multi-axle trucks than do the fleets on I-10 and I-17. Another key parameter is the rate of reloading of dust on the surface from all sources. A third key parameter is the wind field characteristics. The particulate emission factor along a roadway section will depend, in a complex way, on the interaction between these and other parameters.

II. STUDY DESIGN AND METHODS

DESCRIPTION OF SAMPLING EQUIPMENT, GEOMETRY, AND ANALYTICAL TECHNIQUES

Three mobile laboratories mounted in utility trailers were used in the study. Each was equipped with particulate monitoring and meteorological instruments. The primary measurement was real-time PM_{10} concentrations (the mass of particles 10 μm and less in diameter), measured with tapered element oscillating microbalances (TEOM, Rupprecht and Pastashnick Inc.) with PM_{10} inlets. Each TEOM also had a wind-sectored particulate filter sampling system (ACCU system) to collect samples for examining by scanning electron microscope (SEM). Meteorological variables measured at each station were temperature, precipitation, relative humidity, wind speed, and wind direction.

The TEOM has the capability to measure and log real-time fluctuations in particulate concentrations, while the ACCU system allows particulate sampling of discrete sectors of wind direction and wind speed for later analysis and characterization. Also used in the sampling experiment was a 10 m sampling tower, on which were mounted PM_{10} DustTrak (TSI, Inc.) particulate monitors (DustTraks) at 3 and 10 m, as well as a sonic anemometer at 10 m (to acquire 3-dimensional wind data and measure turbulence). During the 2001 and 2002 experiments, a video camera and recorder were placed on one of the trailers to record the traffic load on the freeway. The traffic load and fleet composition were determined by manually counting and classifying vehicles on the videotapes after the experiment.

This equipment was deployed along the Loop 101 Freeway, just south of the Chaparral Road exit in February and March of 2001 and 2002 for a total of approximately 3 weeks. At that location the highway is on the Salt River Pima-Maricopa Indian Community and is flanked on either side by flat agricultural fields with long unobstructed wind fetches to the east and west in excess of 200 m. The setup of the equipment is shown in Figure 1. This site is conducive to this type of experiment, as the freeway direction is due north-south, and the wind pattern in the winter is frequently an east-west slope flow. By placing the three trailers in an east-west array as shown in Figures 1 and 2 , it is possible to quantify the background particulate concentration entering the freeway, and measure the output concentration on the downwind side in real time using the TEOMs. The 10 m tower allowed the research team to quantify the vertical profile of the particulate concentration and measure the wind velocity normal to the freeway, both of which are crucial to understanding the freeway particulate mass flux. The ACCU systems allowed quantification and comparison of the nature of the particles (size, shape, and composition) that originate from the freeway itself with those in the ambient environment.
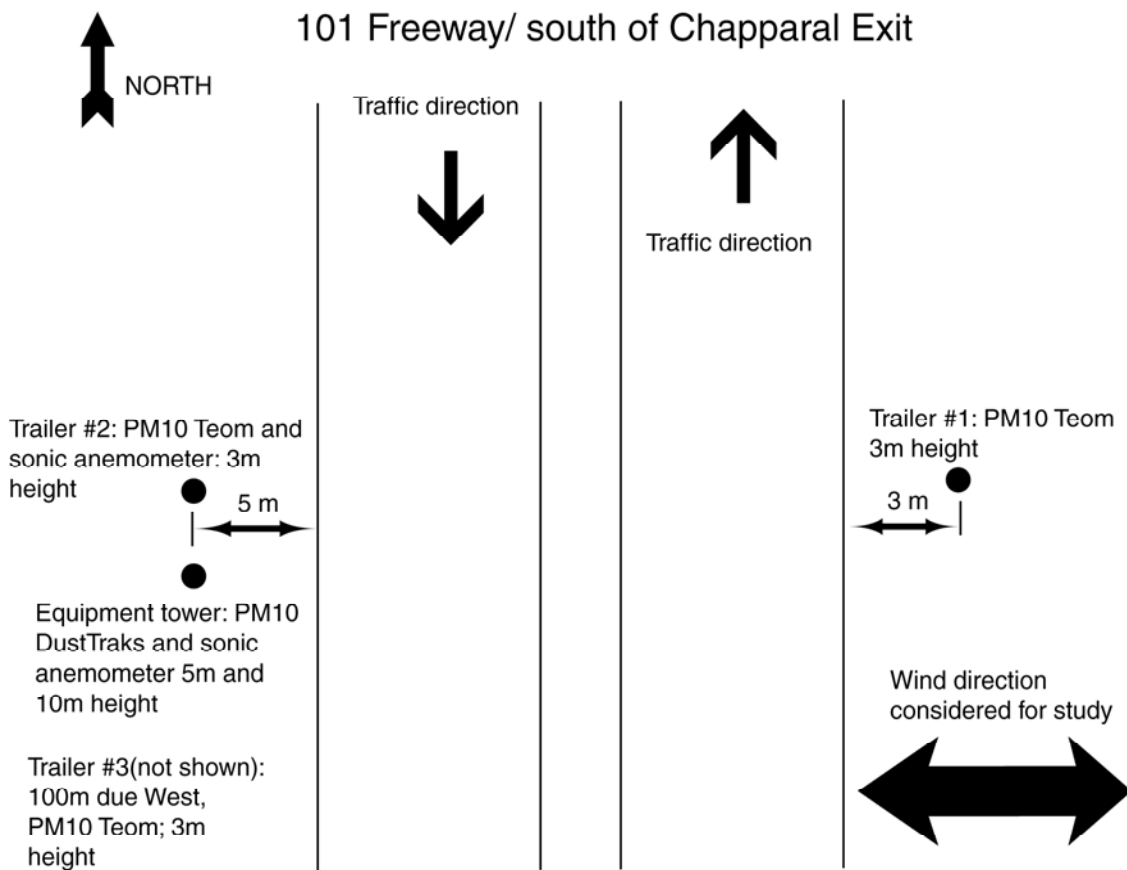
Figure 1: Map view of sampling geometry along the 101 Freeway, at mile 47 near Chaparral Rd. Exit.

Note that the position of Trailer #3 is not shown, but is 100 m due west of Trailer #2. Anemometers were deployed on all trailers at 3 m height, in addition to the sonic anemometers at 3 m on Trailer #2 and at 10 m on the tower. The direction of travel of the traffic is north-south. Traffic was counted and categorized during daylight hours via a video camera looking west on Trailer #1.

Figure 2A. East side trailer with TEOM inlet and anemometer on top, propane generator to side. View looking north.

Figure 2B. West side trailer and tower, view looking north.

Figure 2C. Experimental array, looking east.
> **Note:** From near to far, DustTrak at 200 m from roadway, trailer #3 at 100 m from roadway, trailer #2 and tower at 10 m from roadway, and (barely visible at base of far light pole) trailer #1 on opposite side of roadway.

Figure 2D. Inside one of trailers.
> **Note:** This photo shows (from left to right) TEOM with insulated inlet tubing, TEOM controller and data logger, and ACCU System with 8 filter manifold controlled by TEOM controller. The TEOM controller also logs meteorological data.

Pilot studies were also done in 2001 at two sites along I-10 (near 29th Avenue, at Maricopa County's Greenwood monitoring site, and just north of Chandler Boulevard.) Both sites proved to be unsuitable because nearly buildings and trees deflected surface winds. The equipment was also seriously vandalized at both sites within only a few days of setup. These sites were the most suitable that the team could find along I-10 in the urban area with regard to unobstructed wind fetch, but the study still encountered problems with wind deflection so that, regardless of the vandalism, it would have been difficult to measure dust emission factors at these sites. A number of better sites are located along I-10 as it crosses the Gila River Indian Community, but these are outside of the Phoenix urban area.

The filters used for wind-sectored sampling with the ACCU systems were 47 mm diameter polycarbonate membrane filters with 0.4 µm pores. Polypropylene backing filters with 10 µm pores were used behind the polycarbonate filters to ensure that particles were evenly distributed; otherwise the supporting grid bars of the filter holders can cause uneven distribution.

TEOM DATA

TEOM data was logged every 5 minutes (every 1 second for some periods) and consisted of the following parameters:
1. date
2. time of 5-minute averaged data
3. mass concentration of PM_{10} in units of $\mu g/m^3$, 5-minute average
4. 1-hour average PM_{10} mass concentration, updated every 60 minutes at the hour
5. 8-hour average PM_{10} mass concentration, updated every 60 minutes at the hour
6. ambient temperature in °C
7. ambient pressure in atmospheres
8. wind speed in m/s, 5-minute average
9. wind direction in degrees, 5-minute average
10. active wind sector at end of 5-minute period, based on direction and velocity (see below)

Eight wind sectors were defined for this study. For wind speeds greater than 0.8 m/s and less than 8 m/s, six directional sectors were defined:

Sector 1 = 60-120°
Sector 2 = 120-180°
Sector 3 = 180-240°
Sector 4 = 240-300°
Sector 5 = 300-360°
Sector 6 = 0-60°

Note that the active sector in the data may disagree with logged average wind direction because the logged sector represents the wind direction at the end of the averaging period. The ACCU System filters were operated by solenoid-controlled valves that used the wind speed and direction data as updated every 10 seconds.

Two wind sectors were defined based on wind speed. Sector 7 was defined for wind speeds less than 0.8 m/s. At these low wind speeds, the true wind direction is difficult to determine (the anemometers used are sensitive down to 0.5 m/s). Sector 8 was defined for wind speeds 8 m/s and greater. Above 8 m/s, the generation of wind blown dust from the land surface can become significant; this eliminated contaminating the Sector 1-6 filter samples with dust from high-wind events.

DUSTTRAK DATA

DustTraks were used to measure $PM_{2.5}$ at 3 m height and PM_{10} at 5 m and 10 m on the 10 m tower on the west side of Loop 101. The data are simpler than those from the TEOMs in that only the mass concentration of aerosol in milligrams per cubic meter (mg/m[3)] is measured. The averaging interval was 5 minutes.

While a TEOM directly measures mass, a DustTrak estimates mass based upon the measurement of light scattering: particles pass along a path with a laser and photodectector. DustTraks do not have the warm-up time associated with the TEOMs. However, since particulate concentrations are measured at ambient temperature and relative humidity, particle size and resultant light scattering, and therefore apparent PM_{10} contribution, for hygroscopic species (e.g., ammonium sulfate) will be affected if the relative humidity is sufficiently high. With normal soil dust, hygroscopicity is not an issue. Another issue with the DustTrak is that it is calibrated for standard soil dust with a high single-scatter albedo, so optically absorptive materials like soot with low single-scatter albedo will be undercounted.

When DustTrak measurements of PM_{10} were compared with TEOM values, the two values were generally less the 5 $\mu g/m^3$ apart, and in any event in the field there was short-term fluctuation of particle concentrations due to vehicle turbulence. However, there was no real-time reference for $PM_{2.5}$ with which to compare the DustTrak measurements. Some problems with the measurement of the optically absorptive part of the fine particulates were expected.

SCANNING ELECTRON MICROSCOPE METHODS

Individual-particle samples were analyzed with an automated scanning electron microscope (SEM) (Anderson et al., 1992, 1996). The specific instrument used was a JEOL 5800 SEM with a NORAN Voyager 4 automation/image analysis/X-ray analysis system. A roughly 1 cm square section was cut from near the center of each filter and mounted with conductive carbon tabs on 12 mm aluminum stubs. A carbon film of ~20 nm was deposited on the sample by vacuum evaporation to provide electrical conductivity. Backscattered electron (BSE) images were acquired using an annular, split-ring, semi-conductor detector mounted 10 mm above the sample. Images were digitized and stored in the Voyager system's image memory. X-ray spectra were acquired with a NORAN energy dispersive spectrometer (EDS) with an ultrathin window.

Normal operating conditions are an accelerating voltage of 15 kilovolts (kV) and beam current of 400 picoamperes (pA). Counting times for X-ray spectra acquisition are 60 seconds live-time; relative dead-times are 20-30%. Long counting times allow analysis of many elements in concentrations down to nominal detection limits of 0.1-0.2% by weight (relative to flat, infinitely thick samples); the counting time strongly affects the smallest detectable particle size with respect to composition. For these samples, magnification is 2000x and the smallest particle diameter analyzed was about 0.2 µm. Smaller particles can be analyzed by using higher magnification, but for this study it was important to focus on the larger particles that contribute most to the PM_{10} mass. Image resolution is 1024 x 1024 pixels, with a relative gray-level scale of 0 to 511 (8 bits). Pixel size at this magnification and resolution is 54 nm.

Standard X-ray spectra are acquired by analyzing flat, polished samples of metals, simple oxides, simple salts, and a few well-characterized minerals. Reference spectra are fitted to particle spectra. The values produced, "k-ratios," are then corrected with NORAN's ZAF program to obtain weight percents of the elements, from which atomic fractions of the elements are calculated. The use of flat-sample corrections introduces some systematic error into the particle compositions, but this has little effect on clustering and characterization of particle types. The study compared the results from flat-sample corrections with those from particle correction methods and found no significant difference for average composition of a group of particles of a single type. Elements routinely analyzed are sodium (Na), magnesium (Mg), aluminum (Al), silicon (Si), phosphorus (P), sulfur (S), chlorine (Cl), potassium (K), calcium (Ca), titanium (Ti), vanadium (V), chromium (Cr), manganese (Mn), iron (Fe), nickel (Ni), copper (Cu), zinc (Zn), gallium (Ga), germanium (Ge), arsenic (As), selenium (Se), bromine (Br), zirconium (Zr), cadmium (Cd), Sn (tin), antimony (Sb), barium (Ba), and lead (Pb). Anderson et al. (1992, 1996) discuss further details of the analytical methods for automated microanalysis of particles.

For the automated analysis, approximately 1000 particles 0.2 µm and larger were analyzed for chemical composition, size, and shape. These data were used to determine size distributions, shape distributions, and the relative abundance of chemically different particle types.

A Hitachi Cold Field Emission SEM Model S-4700 was used for high resolution imaging. This instrument has a spatial resolution of 1 nm and has an EDS X-ray detector that was used to qualitatively identify particles by chemical composition.

CLUSTER ANALYSIS OF SEM DATA

Cluster analysis of the SEM data was used to determine the chemically distinct types of particles present in a set of aerosol samples. Clustering of particle data is done with the program EXPLOR (Saucy et al., 1987, 1991; Shattuck et al., 1985, 1991). The Forgy k-means algorithm is the basis for cluster analysis. A similarity measure that represents the angle between vectors from the origin to two points in 24-dimensional composition space is used (Killeen et al., 1981). This measure, s_4, is advantageous in the cluster analysis of chemical data from submicron particles because of their semi-transparency to the electron beam (Saucy et al., 1987). For the SEM results in this study, the value of s_4 used was 20°.

III. PM$_{10}$ RESULTS FROM LOOP 101 AND OTHER SITES

RESULTS: TEOM, DUSTTRAK, AND SEM DATA

Rather than present all the data in hard copy, examples are presented in this report and the other archived data will be available from the research team upon request.

An example of a data file from one of the Loop 101 trailers (east side, starting Feb 22, 2002 and ending Feb 23, 2002) is shown in Appendix A. Initially the mass concentration data is null (or, if other than 0, invalid) until the instrument reaches its operating temperature of 50°Celsius(C). The start and end of TEOM data files signify times when the power was switched off in order to service the electrical generators.

The field experiment in 2002 on Loop 101 produced the most useful data. TEOM data from both east and west measurement sites are archived from Feb 19 to Mar 14 when synoptic weather conditions were suitable.

An example of a DustTrak log is presented in Appendix B. The data log for PM$_{2.5}$ with an inlet at 3 m starts March 3, 2002, at 14:54:50 and ends March 6, 2002, at 12:14:50. The last column is the mass concentration of PM$_{2.5}$ in mg/m^3 and can be converted to more standard units of µg/m^3 by multiplying by 1000. For this time period, the minimum PM$_{2.5}$ was 7 µg/m^3 and the maximum was 88 µg/m^3, a fairly high value.

A total of 23,819 individual particles between 0.2 and 10 µm in diameter were analyzed from samples collected at the Loop 101 site in February 2000 and March 2001. Measured parameters include composition, size, and shape. Because the compositions are determined by fitting sample spectra from small irregular particles to standard spectra from polished flat materials of known composition, the particle compositions never total 100% (most particles are smaller than the X-ray excitation volume and therefore have decreasing total weight percent with decreasing volume). The cluster analysis used partly compensates for this; when expressed as atomic fractions, the centroid compositions have nominal errors on the order of 10% or less. Note that while carbon (C) and oxygen (O) are analyzed, because the filter material is polycarbonate and also has C and O, these two elements are not used. The automated methods always undercount submicron black carbon (primarily soot), so manual imaging as was done in this study is needed to evaluate the abundance, morphology, and mixing state of black carbon. Despite the limitations, individual particle analysis by SEM is very effective in determining that chemically distinct types of inorganic particles are present.

Appendix C has composition, size, and shape data for one of the analyzed samples (the listing of data from all of analyzed samples would take in excess of 1000 printed pages).

PARTICULATE CONCENTRATION BEHAVIOR ALONG ROADWAYS UNDER TYPICAL WIND CONDITIONS

For the purpose of the study objectives, the most interesting periods with regard to freeway PM_{10} emissions come from the frequent intervals when wind speeds are relatively low to moderate (typically less than 6 m/s [12 mph], very common for complex terrain areas in the desert Southwest). Necessary conditions for examining freeway emission factors were wind speeds below 6 m/s, but for reasons described below, not less than 2.5 m/s, and wind directions that came across the roadway at no more than a 45˚ deviation from perpendicular. The influence of the turbulence of passing vehicles makes it difficult to treat the emission data when the wind is closer than 45˚ to parallel with the roadway. The conditions of lowest wind speed (<2.0-2.5 m/s) are a special class that occur for periods on most days at the transition from heating to cooling and from cooling to heating; such conditions of stagnation can also occur at other times, especially at night. While wind conditions (direction, velocity, and stability) have a significant effect on the success of experiments, emissions from the roadway surface occur whenever there is traffic regardless of wind direction or wind velocity.

Evaluation of the PM_{10} TEOM and meteorological data from the Loop 101/Chaparral Road site indicates that there is measurable re-entrainment of particles from the freeway at this site with residual particle concentrations (downwind concentration minus upwind "background" concentration) with speeds in the range 2.5-6 m/s (as low as 2.3 m/s in some cases). Figures 3 and 4 show the wind direction from both trailers overlain by the TEOM particle concentration and wind speed respectively for two typical 24-hour periods. For cross-roadway winds when wind speed is in excess of 2.5 m/s, the wind directions on both sides of roadway are similar and the difference in PM_{10} approaches averages of 20-30 $\mu g/m^3$, except in periods of low traffic where the difference is less. This difference is the contribution of re-entrained dust from the roadway surface plus particles from exhaust and abrasion of vehicle components (the SEM data indicate that dust is dominant). However, note that the wind directions diverge for the two trailers during the morning rush hour when wind speeds are below 2.5 m/s, and also that there is a peak in particle concentration (sometimes reaching >250 µg/m3) that is seen for both sides of the freeway. The wind direction divergence shows that the wind direction measured on the west side of the road is strongly influenced by turbulence of vehicles traveling north, while the east side is affected by the turbulent wakes of southbound vehicles. During the evening rush hour, with higher wind speeds, the two wind direction measurements do not diverge and no significant PM_{10} peak occurs, just the typical cross-roadway difference in PM_{10}. This pattern is a common one for all of the days sampled, broken only by weather conditions when stronger winds(> 6 m/s) are present.

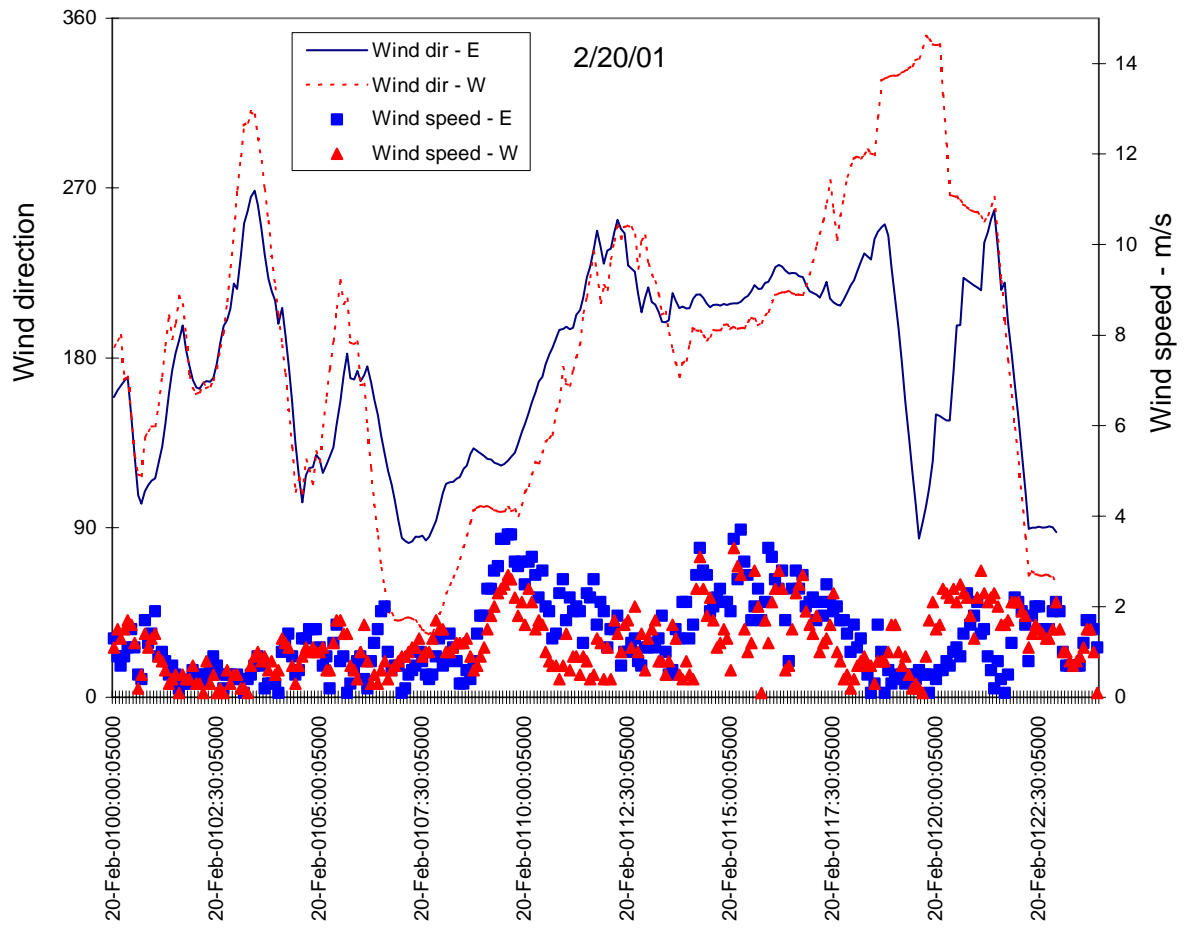**Figure 3. Wind direction and speed during a 24-hour period Feb 20, 2001, Loop 101 Chaparral site.**

Note: divergence of wind direction on east and west sides of roadway when wind speed is below about 2 m/s. This is a typical day for this time of year with wind below 2 m/s for most of the day.
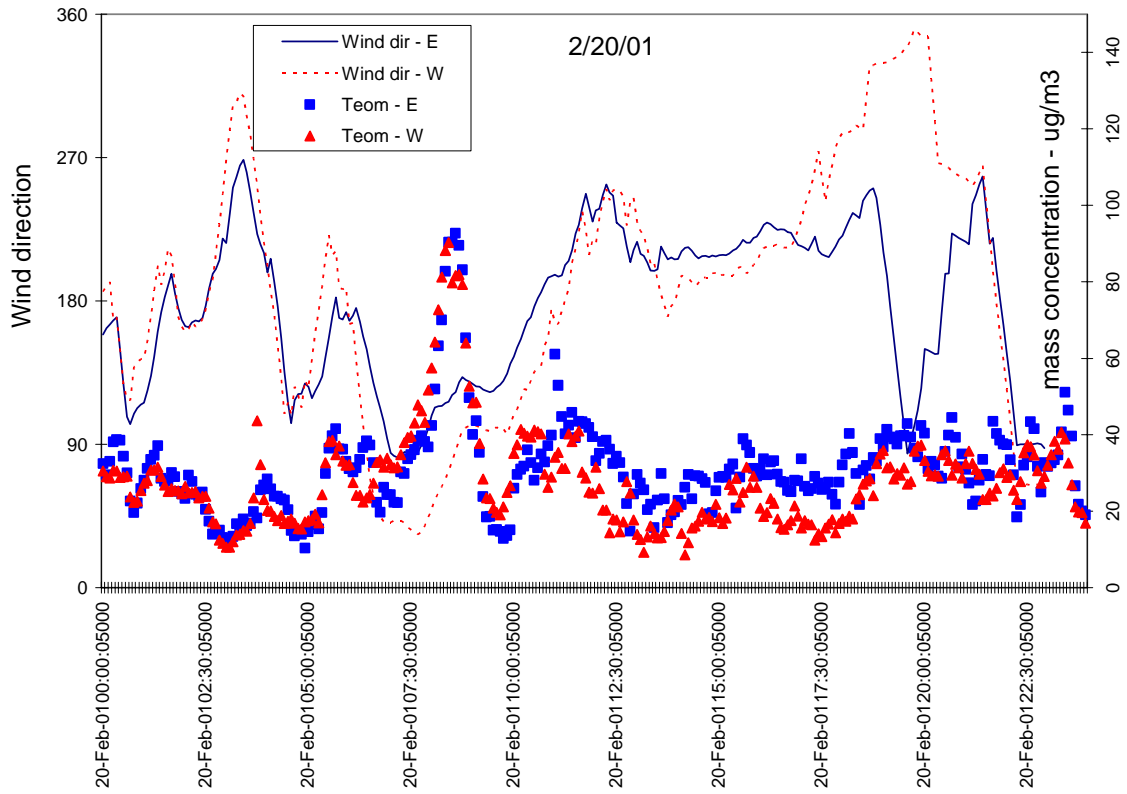
Figure 4. Time versus wind direction (left axis) and PM$_{10}$ concentration in µg/m^3 (right axis).

Figure 5 shows the wind direction measured by two anemometers at 3 m height closest to the freeways as a function of wind velocity. There was a small error (~5°) in initial alignment of the anemometers, which accounts for the deviation of the residual from 0° above 2.5 m/s. It shows that there is a critical ambient wind velocity (~2.5 m/s) necessary to consistently dominate the local velocity regime created by the turbulence of the passing vehicles. However, there are also times when the wind speed is below 2.0 m/s and the wind directions on the two sides agree. The peak PM_{10} concentrations only occur when the wind directions are dominated by vehicle turbulence.

Although typical transportation line-source models assume that the zone of mixing of the roadway extends no more than 3 m from the edge of the pavement, the data indicate the zone of mixing extends at least to the 8-10 m distance from the paved surface that the trailers were placed (because of safety considerations). Otherwise, the influence of the turbulent wakes during low wind speed would not have been observed. There is sonic anemometer data to support this conclusion, although the sonic anemometer measurements were part of a graduate student thesis project that is not yet completed. These observations suggest an important shortcoming in current line-source models; a more detailed study of the zone of turbulence and its structure than was done here is essential for a complete understanding of freeway emissions.
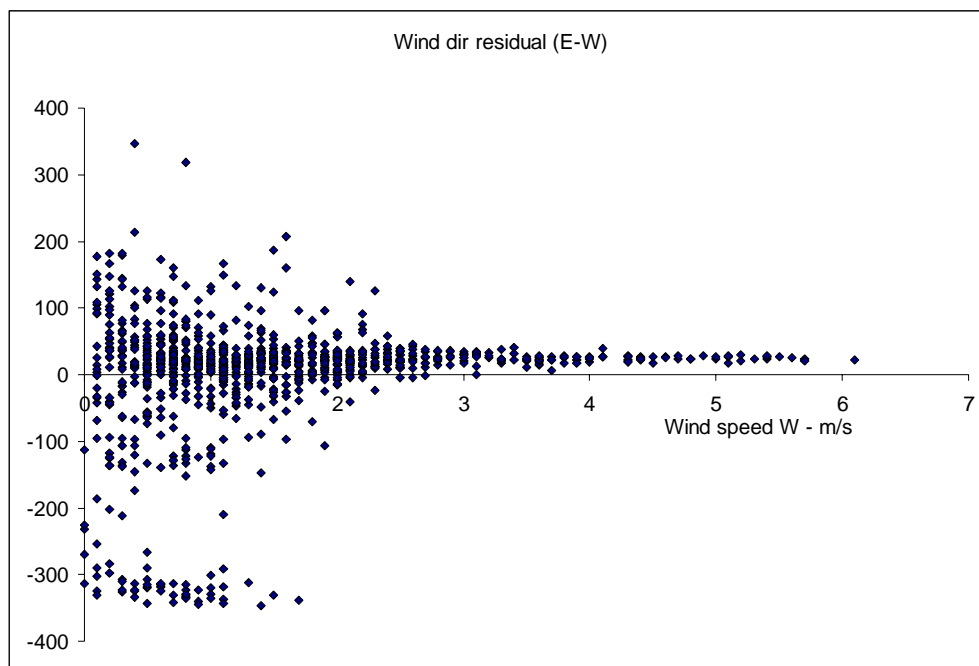
Figure 5. Difference in direction between wind directions (Y-axis) on east and west sides of roadway versus wind speed (X-axis) on the west side.
Note: Above 2.5 m/s, the two directions always agree (a slight error in aligning the anemometer on one side is responsible for the deviation from 0 directional difference above 2.5 m/s). In many cases the wind directions agree below 2.0 m/s, but this generally occurs when traffic is light or traffic speed is very low.

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HORIZONTAL DISPERSION OF PM$_{10}$ AND PM$_{2.5}$ PARTICULATE PLUME NORMAL TO THE FREEWAY CORRIDOR

During the 2002 experiment, a third trailer (Chap W2) was placed ~100 m to the west of the 101 freeway to measure the horizontal distribution of particulates away from the road. Unfortunately, only 5 days of sporadic data were successfully collected, due to mechanical difficulties and the subsequent burglary of the equipment from this trailer. Enough data was collected however to determine the magnitude of the decrease in PM$_{10}$ concentration away from the road. Figure 6 shows the TEOM results for all three trailers for the evening rush hour on March 9, 2002, in. The average wind direction for the period shown is approximately 120 degrees (ESE) with an average velocity of 1.8 m/s. The ambient particulate concentration is well measured by the east trailer (Chap E) and is typical at an average of 15 μg/m3 and does not show a peak in concentration associated with the rush hour traffic, indicating that the prevailing wind is dominating and the particulate concentration measurements are not influenced by turbulence. In contrast, the west trailer (Chap W) next to the freeway shows a peak in concentration at 100 μg/m3, resulting in a residual concentration of ~85 μg/m3 for the rush hour. The ChapW2 trailer also shows a peak in concentration correlating in time with that of ChapW, but is significantly smaller at ~35 μg/m3. This shows that over 50% of the PM$_{10}$ concentration coming from the freeway has dispersed by the time it has traveled 100 m from the roadbed at moderate (~2 m/s) wind velocities normal to the traffic direction.
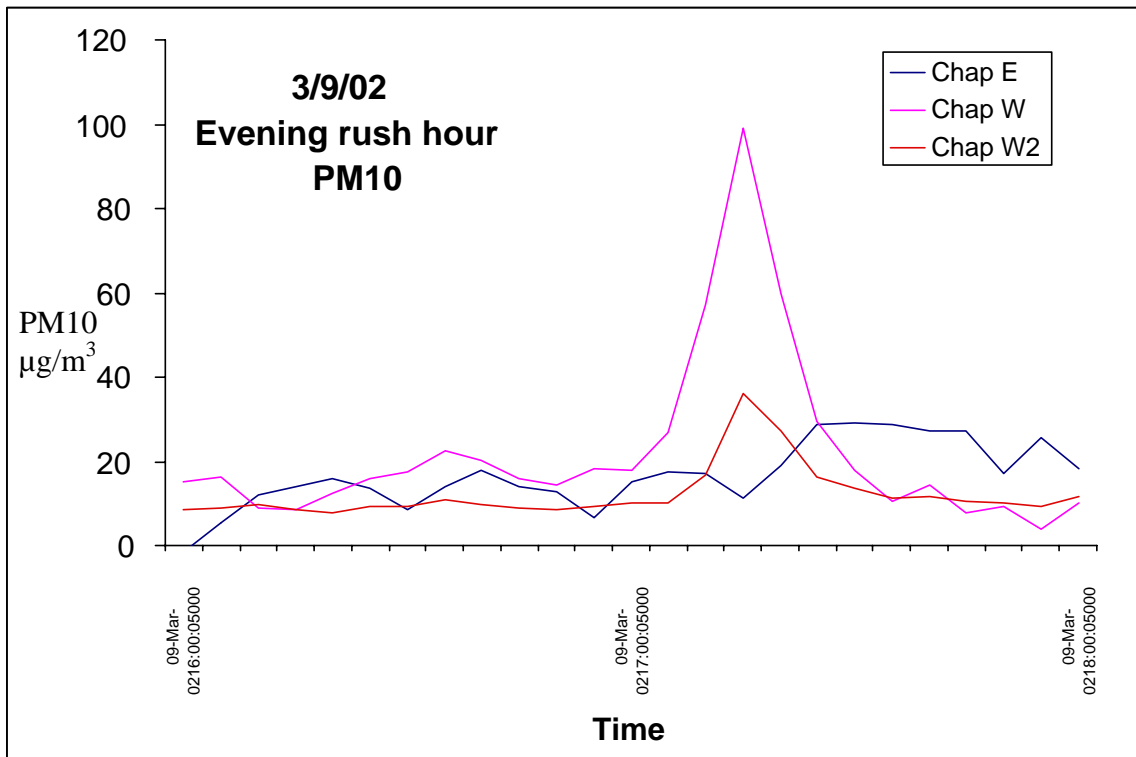
Figure 6. PM$_{10}$ concentration for evening rush hour on Mar 9, 2002.
Note: Average wind velocity was ~120° (ESE), with an average velocity of 1.8 m/s. Note also the flat ambient background measured by trailer E and the significant decrease in concentration at trailer W2 (100 m west of freeway)

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The $PM_{2.5}$ (particles smaller than 2.5 microns) concentration was also monitored at this time in ChapW and ChapW2 trailers using DustTraks. The results are more ambiguous than those for PM_{10} however. The $PM_{2.5}$ concentration for the same evening rush hour period on March 9, 2002, is shown in Figure 7. Also shown is the $PM_{2.5}$ data for the 24-hour period that includes the evening rush hour. The concentration levels of $PM_{2.5}$ next to the freeway are not significantly different from those found 100 m away. The differences, especially at low concentrations, mostly are within the error of the DustTraks.

Figure 7A. $PM_{2.5}$ concentrations as measured by DustTraks at ChapW and ChapW2.

Figure 7B. Detail of evening rush hour.

THE RATIO OF PM$_{2.5}$ TO PM$_{10}$
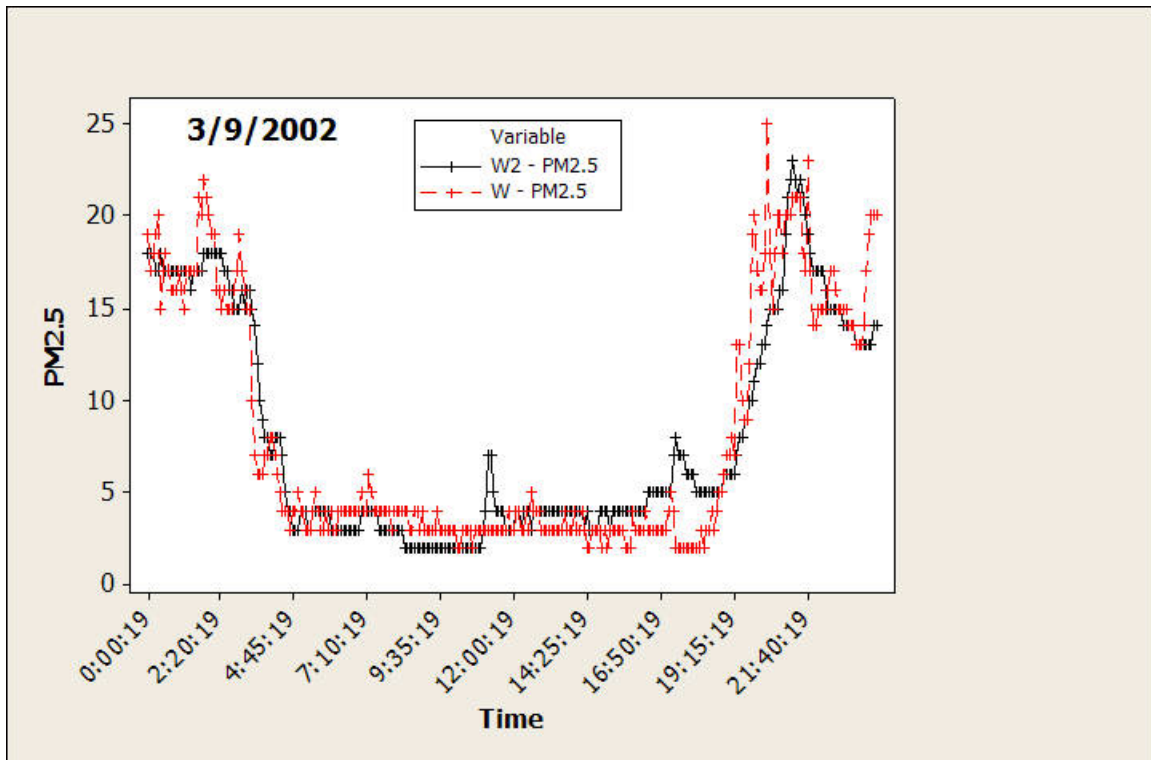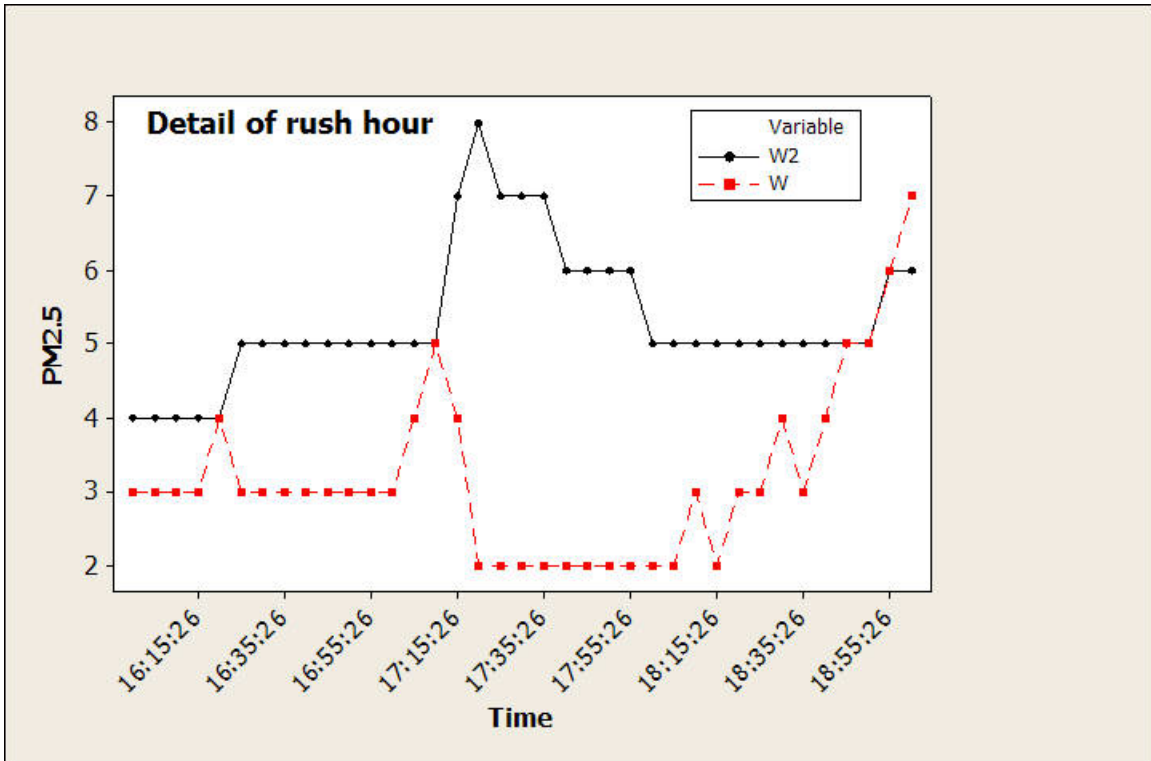
Smaller particles have lower settling velocities, so at least under some circumstances, the lack of a horizontal gradient for PM$_{2.5}$ when a strong PM$_{10}$ gradient is present is reasonable. However, the ratio of PM$_{2.5}$ to PM$_{10}$ suggests some complexity that needs further examination. (Again, possible problems with DustTrak measurements of fine, optically absorptive particles like soot from exhaust need to be kept in mind.)

Simultaneous measurement of PM$_{2.5}$ and PM$_{10}$ was done on the west edge of the roadway, using trailer ChapW, in March 2002. Good data without large gaps were obtained over 1066 5-minute intervals during the period of March 6-11. Scatterplots of PM$_{10}$ and PM$_{2.5}$ versus wind speed (Figure 8) reinforce the hypothesis that high concentrations occur during periods when the wind speed is below a critical value. In this period, the critical value for PM$_{10}$ is about 2.0 m/s, but for PM$_{2.5}$ is about 2.5 m/s. Although low wind speed is a necessary condition for high aerosol concentrations, high concentrations do not always accompany low wind speeds. Other factors, including traffic count, vehicle fleet composition, and vehicle speed must be important. However, periods were observed when conditions seemed appropriate for high aerosol concentrations but a concentration peak did not occur.
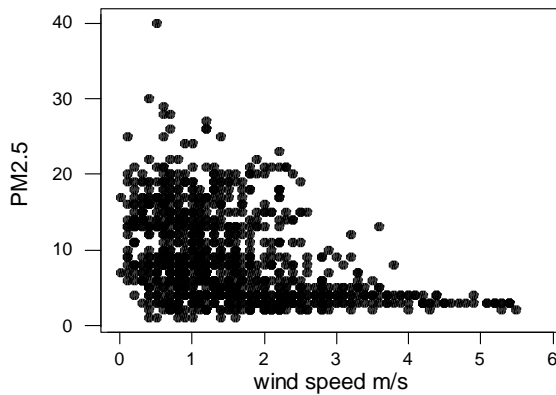

Figure 8A. Scatter plot of PM$_{2.5}$ concentration versus wind speed for 1066 5-minute intervals for Mar 6-11, 2002.
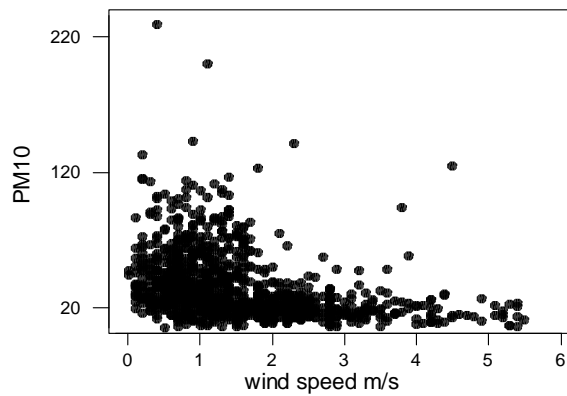
Figure 8B. Scatter plot of PM$_{10}$ versus wind speed for 1066 5-minute intervals for Mar 6-11, 2002.

The ratio of $PM_{2.5}$ to PM_{10} for March 6-11 is shown in Figure 9. The range of values is from less than 0.1 to 1.0. When wind speeds were higher than the threshold, $PM_{2.5}/PM_{10}$ is low. The ratio is also low during some periods of low wind speed. All of the high $PM_{2.5}/PM_{10}$ values occurred during low winds speeds and such conditions sometimes lasted for several hours.

At least two sources of fine particulates could be contributing to freeway $PM_{2.5}$. During low wind speed periods with heavy traffic, the vehicle turbulence could trap exhaust particles, soot plus organics that were not measured, and allow their concentration to build up. Also, since many large soil-dust particles are aggregates of smaller particles, the mechanical action of vehicles passing over particles on the pavement could tend to disaggregate soil dust particles into smaller component particles. Additional measurements including direct determination of elemental carbon concentrations are needed to resolve the questions that remain concerning $PM_{2.5}$ behavior during low wind speed.

The variability of the ratio during low wind periods may be due to variability in the settling rate of large particles. The continuity and strength of the turbulence from passing vehicles should be strongly influenced by both the frequency of larger vehicles and their speed; the latter was not measured. A careful study of the turbulence during low wind periods would be needed to better understand this issue.
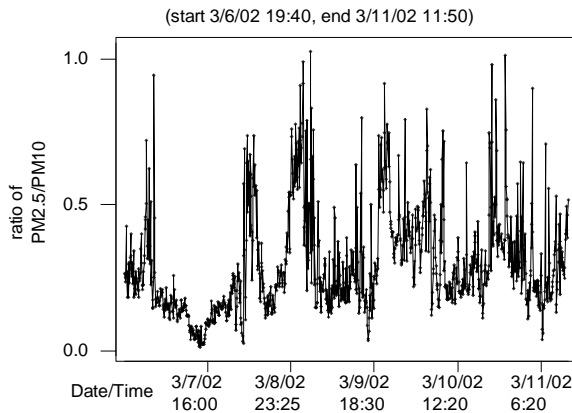
Figure 9. Plot of $PM_{2.5}/PM_{10}$ versus time for Mar 6-11, 2002.

DETERMINATION OF VERTICAL PROFILES OF PARTICLE CONCENTRATION AND WIND VELOCITY

Important to the understanding of the particulate behavior near major urban freeways is the vertical distribution of particulates, and the influence of wind velocity changes as a function of height. Using the TEOM measurements at 3 m as well as DustTrak determinations at 5 and 10 m, a model for the vertical distribution of PM_{10} particulates has been developed and is shown in Figure 10. The values at 3 and 5 m have been averaged and normalized to the values measured at 10 m. There is no significant difference in the concentration between 5 and 10 m, while there is an increase of a factor of ~4 between 3 and 5 m. This indicates a strong gradient in particulate concentration at about 3-5 m. The wind velocity was measured both at 3 and 10 m and the model for the vertical gradient is shown in Figure 11. A no-slip boundary at the ground is assumed.

Figure 10: Average normalized vertical distribution of PM_{10} particulates to 10 m.

Note: Error bars are 1 std deviation.

Figure 11. Average normalized wind velocity as a function of height to 10 m.

Note: A no-slip condition is assumed (v=0 at 0 m) and all values are normalized to velocity at 10 m. Error bars are 1 std deviation.

Table 1. One hour average simple emission factors for 101 freeway.
*- highlights wind speeds below threshold value (and therefore not true emission factors)

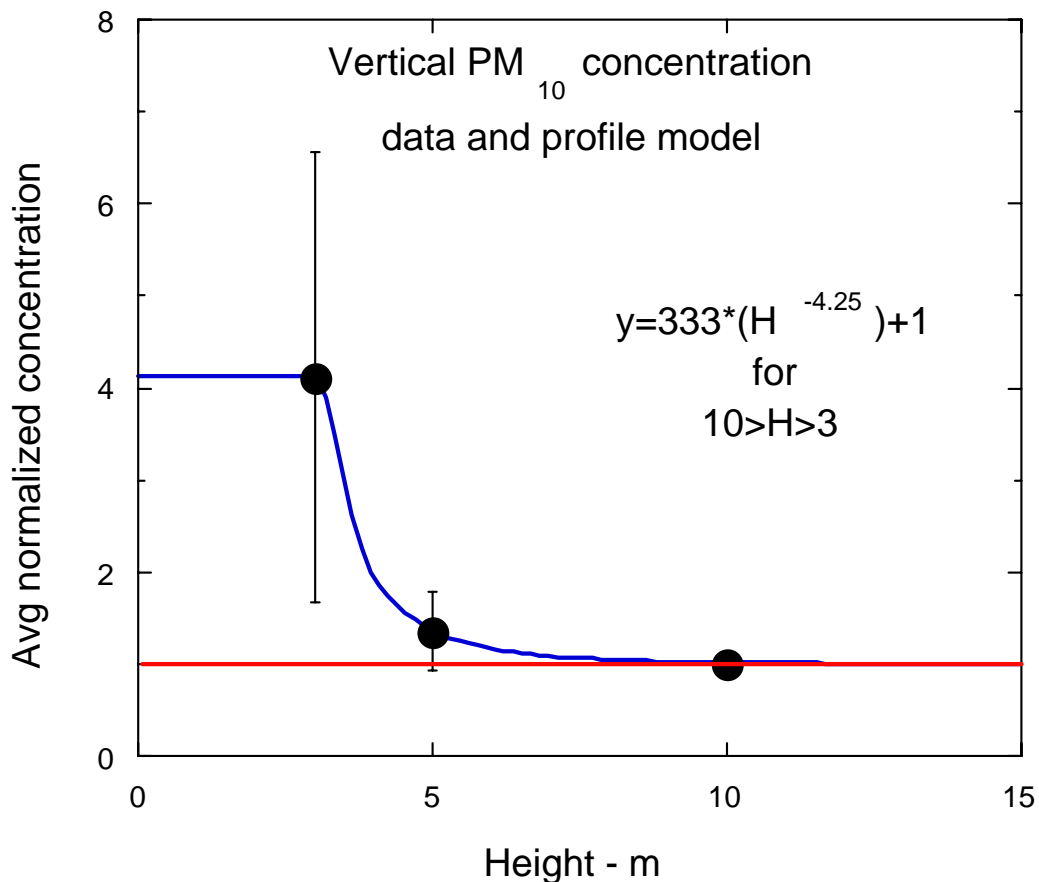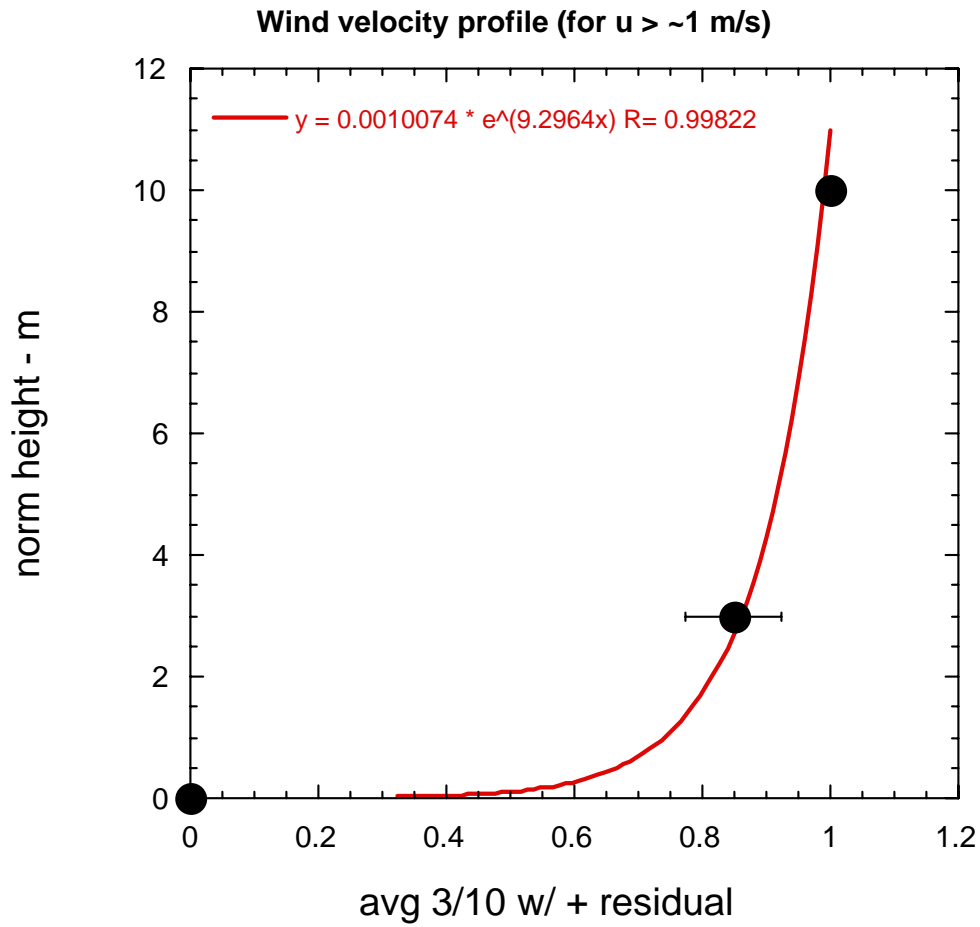| Date/1 hr period	E gVKT^{-1}	Total vehicles	Avg wind speed m/s	Avg wind direction (E side) deg	Avg wind direction (W side) deg
3/7/02					
7-8 am	0.007*	15846	1.0*	118	47
8-9	0.026*	11792	1.0*	85	64
9-10	0.040*	9606	1.9*	143	138
2-3 pm	0.255*	10266	1.9*	253	260
3-4	0.120	11714	2.3	265	269
4-5	0.085	11764	2.6	264	276
3/9/02					
11-12 pm	0.180	9290	4.4	68	67
12-1	0.109	9042	2.5	76	73
1-2	0.042*	8644	1.8*	85	69
2-3	0.039*	8882	2.1*	103	65
3-4	0.001*	9122	1.2*	159	176
4-5	0.013*	9270	1.5*	158	140
3/11/02					
7-8 am	0.067*	12650	1.1*	220	245
8-9	0.037*	10274	0.9*	143	120
9-10	0.013*	8590	1.0*	188	191
3/12/02					
10-11 am	0.094*	8338	1.8*	106	96
11-12 pm	0.059*	8668	1.5*	123	111
12-1	0.037*	8438	2.2*	187	191
1-2	0.001*	8774	2.2*	186	193
3-4	0.023*	11192	2.1*	204	222
4-5	0.058*	11696	1.8*	262	280
5-6	0.044*	11308	1.8*	287	287
3/13/02					
7-8 am	0.018*	12198	1.3*	50	32
8-9	0.020*	11208	0.8*	114	51
9-10	0.090*	9177	1.8*	148	141
12-1 pm	0.010	9086	3.6	191	200
1-2	0.110	8970	2.8	223	230
2-3	0.200	9944	3.8	267	270
3-4	0.001	11406	5.4	239	240
4-5	0.120	11560	5.6	233	237

CALCULATION OF EMISSION FACTORS

Several parameters are necessary for the calculation of PM_{10} emission factors for the site. These include 1) an accurate count of the traffic load in both directions, 2) a measure of the freeway contribution to the particulate concentration, 3) wind direction, 4) wind velocity, and 5) an estimate of the vertical profiles of particulate concentration and wind velocity. All of these parameters have been successfully measured and the results of the calculations are presented here.

Simple Emission Factor

The simplest emission factor calculation is carried out by assuming that there is no vertical change in the particulate concentration or the wind velocity. The formula for this calculation is:

$$E = \frac{\Delta C * \left(\left| v \sin \Theta \right| \right) * h * w * 3600}{T}$$

where E is the emission factor in $gVKT^{-1}$, ΔC is the absolute residual particulate concentration between the east and west trailers (i.e., the freeway contribution to the concentration), v is 1 hr average wind velocity at 3 m, Θ is the 1 hr average wind direction in degrees (0-360), h and w are the height and width of the box being considered (10 and 1000 m respectively), and T is the total number of vehicles per hour. A factor of 3600 seconds per hour (s/hr) is also needed to convert the wind velocity from m/s to m/hr. The results for periods in which the traffic load was determined are given in Table 1.This method for calculating the emission factors assumes that there is no vertical dependence in the distribution of either the wind velocity normal to the freeway or the PM_{10} concentration. Using the vertical profiles described in the previous section, but assuming a linear behavior between the three measuring heights (3, 5, 10 m), calculations of the emission factor have been made that integrate the profile over these three heights.

The emission factor calculated for low wind speed periods is only an apparent emission factor. Because the transport of aerosols is in the direction of traffic at least at some times during low wind speed events, any measurement of the emission factor must be suspect. When the vehicle turbulence domination stops, even if only briefly, then a high apparent emission factor may also occur as the plume of previously trapped aerosol is transported to one side. The calculated emission values during low wind periods and immediately after low wind periods are only apparent emission factors and cannot be included in a regression versus wind speed.

Eight of the above periods had average wind speeds of at least 2.3 m/s (although this does not guarantee stable conditions of wind speed and direction). The average of these values is about 0.1 $gVKT^{-1}$, a value reasonably close to the modeled value of 0.2 $gVKT^{-1}$ of Venkatram et al. (1999) given that they estimated an uncertainty of about a factor of 2. If the two low outliers of the eight values are eliminated, the simple emission factor is 1.3 $gVKT^{-1}$.

When the vertical profiles of wind speed and PM_{10} concentration are taken into consideration, the calculated emission factor is about 60% of the simple emission factor. This "profiled" emission factor of about 0.06 1 $gVKT^{-1}$ should be a more accurate representation of actual emission per vehicle. However, since current line source models use that simple assumption of homogeneity up to 10 m, in such cases the simple emission factor may be more appropriate.

There is no expectation that the emission factor is constant. It can depend upon factors such as fleet composition and speed, plus of course the amount of loading of entrainable particles on the roadway surface. One of the objectives was to evaluate fleet composition and vehicle speed effects. One would do this by making measurements of the emission factor over enough periods for which the fleet composition varies, particularly with regard to high-profile trucks. Then the relative emission factors for cars and trucks could be determined by a regression of the variables. However, the number of acceptable measurements of the PM_{10} emission factor was limited by the presence of wind speeds below the critical threshold for the majority of the time the field experiments were conducted in both 2000 and 2001. Also, the vehicle fleet composition did not change much along Loop 101 except at night when the video camera was not operational. The experiment would need to be repeated with the addition of video cameras that could operate under low light conditions to meet this objective.

For peak traffic periods with a volume of 11,000 vehicles per hour, the mass of PM_{10} generated by re-entrainment and vehicle exhaust along 1 km of freeway would be 1100 g for the simple case or 600 g for the case in which the vertical profile is considered. Since much of this appears to be soil dust, some mechanism (e.g., track-on of dust by construction vehicles – observed at night, but not measured due to video camera limitations) must frequently reload the roadway surface. Otherwise, the dust on the roadway surface would soon be lost and the emission factor would gradually drop.

COMPARISON WITH MODELED EMISSION FACTORS

Paved roadway emissions are the sum of exhaust, brake and tire wear, and re-entrained road dust. The experimental work presented here has shown that the emission factor that accounts for all three vehicular sources is within the range of 0.061 g/VKT to 0.1 g/VKT, the former value based on measured vertical dispersion through the 10 m boundary layer and the latter assuming equal concentrations throughout the 10 m. These measurements compare favorably with the estimates from the standard models, which provide values of 0.054 g/VKT to 0.061 g/VKT, depending on the percentage of heavy-duty diesel truck traffic. These modeled values are discussed below.

The sixth version of the U. S. Environmental Protection Agency's vehicular emissions model, MOBILE6.2, is the one presently in regulatory use (EPA, 2003). For particulate emissions, the model provides emission factors for tailpipe and brake and tire wear, but not for re-entrained dust, whose estimates depend on a simple equation based mostly on silt loading (EPA, 2003). In this comparison, MOBILE6.2 was run at a speed of 55 mph, with full Maricopa County Inspection and Maintenance credit, and for calendar year

2002. Notice that heavy-duty diesel trucks emit nearly 20 times as much particulates as light duty gas vehicles. The overall exhaust emission factors double from 0.017 to 0.035 g/VKT as the percentage of diesels increases from 2 to 10%.

Table 2. Exhaust, brake and tire wear, and re-entrained dust emission factors from freeways.

Exhaust, brake & tire wear EF	g/VKT
Heavy-duty diesel vehicles (HDDV)	0.237
Light-duty gasoline vehicles (LDGV)	0.012
HDDV percentage in traffic stream	
HDDV 2%; LDGV 98%	0.017
HDDV 5%; LDGV 95%	0.024
HDDV 10%; LDGV 90%	0.035

The exhaust, brake, and tire wear emission factor for the Loop 101 was in the range of 0.012 to 0.024 g/VKT, depending on the degree of heavy diesel traffic.

The quantity of particulate emissions from resuspension of loose material on the road surface due to vehicle travel on a dry paved road may be estimated using the following empirical expression:

$$E = k * (sL / 2)^{0.65} * (W/3)^{1.5} - C \quad , \text{ where}$$

$E =$ particulate emission factor in g/VKT,

$k =$ particle size multiplier for particle size range and units of interest (k = 4.5 for PM_{10} and g/VKT),

$sL =$ road surface silt loading (grams per square meter) (g/m^2),

$W =$ average weight (tons) of the vehicles traveling the road (national average is 3 tons), and

$C =$ emission factor for 1980's vehicle fleet exhaust, brake wear and tire wear (for PM_{10} and g/VKT, C = 0.1317).

The emission factors for the exhaust, brake wear and tire wear of a 1980's vehicle fleet (*C*) was obtained from EPA's MOBILE6.2 model.

The only variable of concern in this equation is the silt loading. Silt, defined as 75 microns and smaller, is usually measured by carefully vacuuming and weighing the particles from a measured pavement area. Arizona measurements are given in Table 3. Generally, the higher the traffic is, the lower the silt loading. Silt loading on freeways

would be expected to be quite low. Choosing a value from the lowest end of the Arizona measurements would not be workable, however, since a value of 0.0177 g/m^2 is necessary to counter the constant and at least produce a zero emission rate. Values higher up the distribution produce the following emission rates:

Silt loading (g/m^2)	Emission Factor (g/VKT)
0.02	0.018
0.025	0.053
0.03	0.087

Table 3. Silt loading from paved roads in Arizona (grams per square meter).

E. McKellips & Olive	0.014	busy arterial
Anklam Rd, St Mary's Rd.	0.014	mod arterial
Oracle Rd S. of Kanmar	0.014	busy arterial
Ina Rd E. of La Cholla	0.021	busy arterial
17th Ave and Highland	0.028	local
22nd St E. of Camino Seco	0.028	busy arterial
Indian School/28th St.	0.035	busy arterial
28th St & Glenrosa	0.035	local
43rd Ave & Vista	0.042	busy arterial
3rd & Miller	0.070	local
South Central	0.084	mod arterial
59th Ave & Peoria	0.098	busy arterial
Mesa Drive	0.098	mod arterial
La Canada, N. of Orange Grove	0.105	local
Ft. Lowell E. of Alvernon	0.112	mod arterial
51st Ave S. of Bridge	0.120	busy arterial
Broadway/Central	0.126	busy arterial
Orange Grove E. of C. dl Tierra	0.160	mod arterial
W. Broadway 38th Dr	0.240	mod arterial
Apache (9th/10th Streets)	0.279	busy arterial
19th Ave S. Lower Buckeye	0.380	busy arterial
Speedway Blvd E. of Pantano	0.398	busy arterial
Avalon & 25th	0.523	local
19th Ave S. River N Broadway	0.570	busy arterial
6th Ave & 28th St	1.269	arterial
Lower Buckeye W. 35th Ave	2.100	mod arterial

Adding the re-entrained emission rate from the 0.025 silt loading of 0.053 to the exhaust, and brake and tire wear emission rate with 2% heavy-duty diesel vehicles of 0.017, gives a combined emission rate of 0.07 g/VKT, within the 0.061 – 0.1 g/VKT ranges determined experimentally. Comparison of the Loop 101 emission factors with recent work in California is also reassuring.

Table 4. Combined Paved Road Emission Factors in g/VKT (ARB, 2001).

	PM_{10}	$PM_{2.5}$
Local	0.076	0.058
Collector	0.032	0.024
Arterial	0.075	0.037
Freeway	0.055	0.035

In summary, the experimentally determined emission factor for PM_{10} from paved roads in this work is consistent with both the standard models and other experimental work.

PARTICLE TYPES FROM SEM ANALYSIS

The particle types found in the analyzed PM_{10} samples from the Loop 101 site are listed in Table 5. The relative concentrations are in particle number and not mass (this analysis method does not directly measure mass; particle volume can serve as a proxy for mass, and is approximated by multiplying the 2-dimensional particle areas by the corresponding "widths," the smaller of the two measured particle axes).

**Table 5. Particle types in east-west sectors from
20 analyzed samples at Loop 101 site.**
Percents are relative number concentrations, 23,819 total particles.

Particle type	Number %	Comments
a. Carbonaceous	8.2 %	Soot, rubber fragments, etc.
b. Aluminosilicates	34.2 %	Soil dust – clays and other minerals
c. SiO2	7.0 %	Soil dust - quartz
d. Ca-Si dominant	4.0 %	Concrete and aggregates of soil dust and CaCO3
e. Fe dominant	15.4 %	Multiple origins possible: engine wear, natural Fe oxide, and Fe oxide from foundries
f. Ca dominant	3.6 %	Cement and natural CaCO3
g. Ca sulfate	1.2%	Agriculture and natural soil component
h. Na dominant	16.5 %	Interpreted as Na from fuel additive. Manual SEM observations indicate these are soot aggregates with minor Na.
i. Na with Cl	1.2%	Appears to be sea salt from long-range transport, some of which is partially reacted to Na sulfate. Common minor type in Phoenix area.
j. Na-Cr and Na-Cu	0.9%	Unusual types not previously observed in Phoenix area, possibly of vehicle origin
k. Ca-Na	1.6 %	Possibly aggregates of Na and Ca types
l. Na-S	4.4%	Reaction products and (h) or (i) with sulfate
m. Fe-Cu-Ba-Ti	1.3%	Unusual type not previously observed in Phoenix area
n. Sulfate	0.4 %	Ammonium sulfate from photo-oxidation of SO2

Because the soil-dust types have significantly larger mean volumes than most of the other types, the particle volume is dominated by soil dust types and therefore the mass is also dominated by soil dust. For instance, samples from sector 4 on the east and west sides of Loop 101 on March 9, 2002, have average volumes for silicates ([b] and [c] in Table 5) of 11.42 μm^3 on the east side and 11.64 μm^3 on the west side (sector 4 faces west, so that particles collected on the east side have come across the freeway or originated from freeway emissions). The number concentrations of silicates on the two sides differ by 14%, probably not a statistically significant difference given all the complicating factors. Type (h) (soot with minor Na as the only detectable element other than C and O) particles have average volumes of 0.62 μm^3 on the east side and 2.81 μm^3 on the west side, but the number concentration of Type (h) particles is 226% higher on the east side compared to the west. This suggests that either Type (h) particles are reduced in size by some process involving the freeway or that the freeway is a source of small Type (h) particles. This is also complicated by a number of other factors. Aggregation of major particle types is observed to be common and there is indirect evidence that the aggregation of soot and mineral dust occurs in the turbulent zone of the freeway; Figure 12 is a secondary electron image of a typical aggregate. Other examples are in the images in Appendix D.
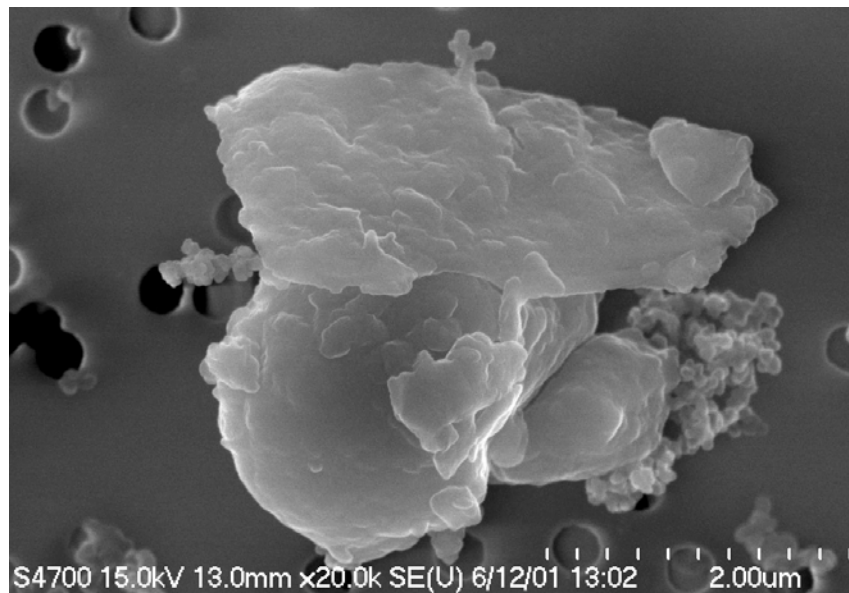

Figure 12. Secondary electron image of aggregate soil dust particle with attached elemental carbon (soot).

> **Note:** Sample also contains at least two other types of elemental carbon as separate particles. Holes are 0.4 µm holes in filter. February 21, 2001, Loop 101. (Enlargement of this image is in Appendix D.)

There are many types of carbonaceous particles; however, not all are soot. Figure 13 is an image of a rubber fragment, typical of tire wear. Soot is formed by many different types of combustion and so can vary in both morphology and composition with regard to minor elements. Some of the key minor elements are K, Na, Fe, and Mg. Soot from biomass burning tends to contain K. Soot from coal combustion frequently has Fe and Mg. Because Na is used as a Pb substitute in some vehicle fuel mixtures, minor Na in soot may be indicative of vehicle exhaust. The high concentrations of soot with Na in the freeway samples suggest this is the case.
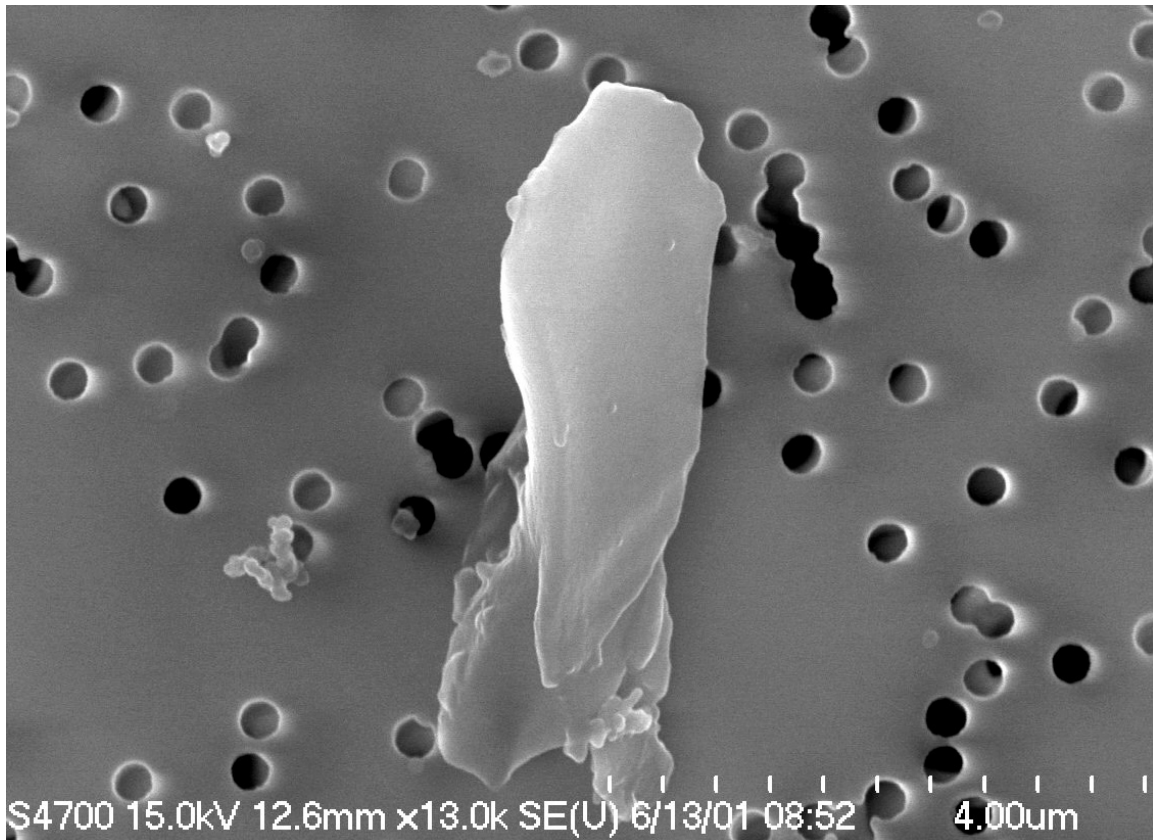

Figure 13. Secondary electron image of rubber fragment (large central particle) with smaller EC particles both aggregated and as separate particles. Feb 21, 2001, Loop 101.

Fe-rich particles have at least three possible sources. A small amount of Fe oxide is in normal soil. There are also industrial sources of Fe oxide and recent work from the Arizona Department of Environmental Quality (Anderson, unpublished data) shows that spherical Fe oxide particles are abundant in SW Phoenix. The hypothesized source is a scrap metal foundry. The third possible source is from vehicles, predominantly from engine wear and perhaps also from tire wear. An Fe dominant particle that is non-spherical and does not appear to be from soil dust is shown in one of the images in Appendix D; many similar particles are present in the aerosol are hypothesized to be of vehicular origin.

Particles with high Ca and Si can result from wear of the concrete road surface, from cement block and pipe manufacture (or other use of cement), or from the natural aggregation of calcium carbonate and silicate minerals. The concentration of Ca-Si particles in these samples is not significantly greater than that observed in other studies have conducted in Arizona. With the exception of the unusual type (m) (Fe-Cu-Ba-Ti), the other minor aerosol types are commonly found in the Phoenix aerosol. Type (m) is of unknown origin.

The particle types that set the freeway aerosols apart from others are the Na-bearing carbonaceous types and the non-spherical Fe-dominant types, both probably directly related to vehicles. However, as already stated, the silicate and aluminosilicate types dominate the PM_{10} mass because they have larger diameters combined with high number concentrations. The majority of soil dust particles observed with high-resolution imaging have at least some small soot attached to them. In the supermicron particles of all types, aggregation of multiple particle species is extremely common.
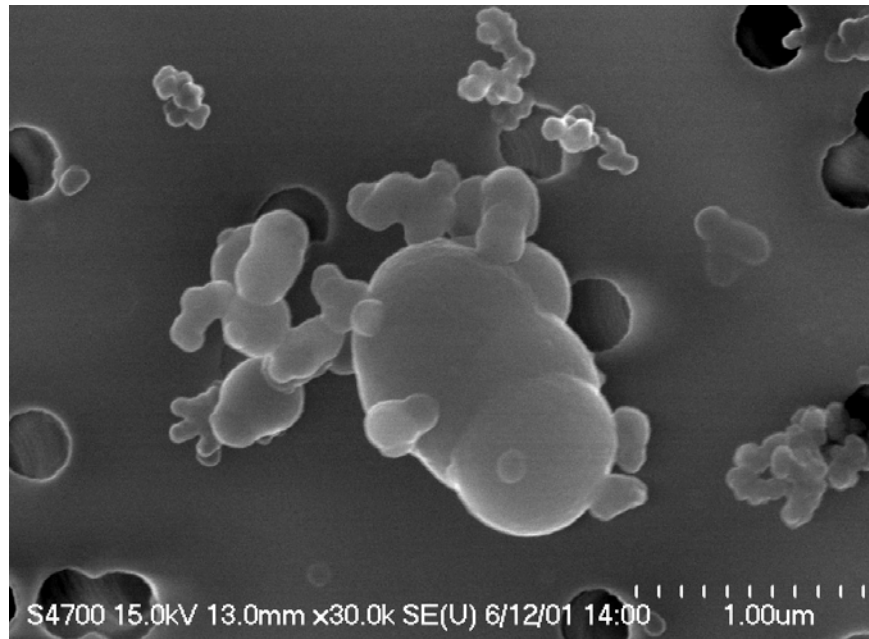

S4700 15.0kV 13.0mm x30.0k SE(U) 6/12/01 14:00   1.00um

Figure 14. Secondary electron image of two types of EC (soot).
Feb 21, 2001, Loop 101.

Figure 15 is a normalized size distribution of the difference between size distributions on the upwind and downwind side for Sector 4 on Feb 21, 2001. For this sample, most of this residual (which represents the aerosol emitted from the freeway) is mineral dust. Note that most of the particles are smaller than 2 μm diameter and therefore will be part of both PM_{10} and $PM_{2.5}$. These and similar data suggest the disaggregating of larger soil particles discussed earlier. The generation of particles in the $PM_{2.5}$ size range is of significance because these particles can stay suspended in the boundary layer for a longer time and therefore make more impact on the regional aerosol than if the particles were larger.

The ability to use the sectored samples to determine the size, shape, and composition of re-entrained particles from the roadway surface is limited because of the frequent low sine speed periods. In any future experiment, it would be better to take unsectored samples for short time intervals (10-15 minutes) for SEM analysis and then choose those samples for which the wind conditions are favorable.
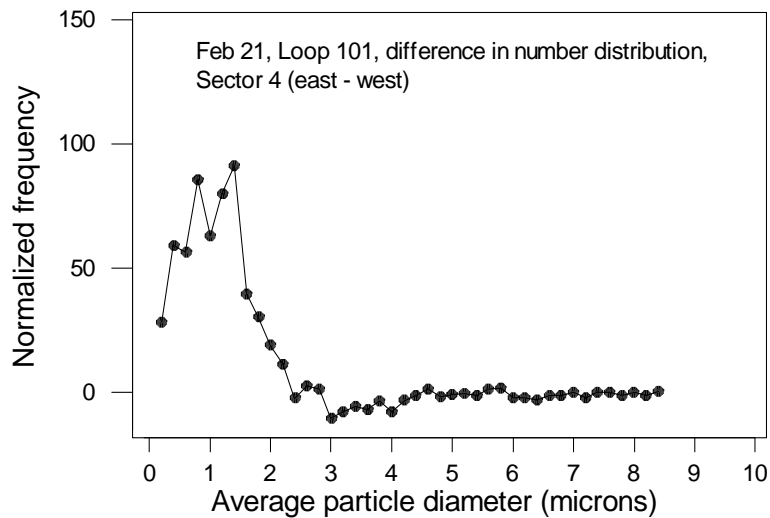

Figure 15. Size distribution of emitted freeway particles determined by subtracting the upwind background size distribution from the downwind size distribution for Sector 4.

IV. CONCLUSIONS

With regard to the project objectives, the following conclusions can be made:

Objective 1: *To determine* PM_{10} *emissions factors for total vehicle-related particulates on major roadways in the Phoenix urban airshed.* The total vehicle-related emission factor measured at the Loop 101/Chaparral Road site was about 0.1 gVKT^{-1}, assuming a simple model of uniform mixing to 10 m height and uniform wind speed. The emission factor is not a constant and could be higher or lower, especially if the loading of the roadway surface with dust varied. If the true vertical profile of wind speed and aerosol concentration is considered, the emission factor is about 0.06 gVKT^{-1}.

Objective 2: *To determine* PM_{10} *emissions factors for re-entrainment of mineral dust particles from major roadways including data by vehicle type and speed so as to assess the impact on the ambient urban aerosol.* The periods when the experiments were run were strongly dominated by low wind speeds. That, coupled with the relative homogeneity of the vehicle fleet composition on Loop 101 during daylight hours, made it impossible to perform the data regressions needed to quantify the effects of vehicle type and speed. An experimental site with more variability in fleet composition and better experimental wind conditions are needed if this is to be accomplished in future research.

Objective 3: *To determine the downwind contributions of roadway particles to* PM_{10} *at distances of up to 100 m, so as to assess the local impact of freeways on adjacent residential areas.* There are significant horizontal PM_{10} gradients on the down wind side of the freeway when the concentration along the roadway is significantly higher than the background level. At 100 m from the roadway, the concentration is 50% or less of the concentration 3 m from the roadway. $PM_{2.5}$ does not seem to behave in the same manner. During the times when we were able to make $PM_{2.5}$ measurements at 100 and 200 m from the roadway, no significant horizontal gradients were observed.

Objective 4: *To determine whether re-entrained mineral dust is aggregated with significant amounts of carbonaceous material.* Almost all mineral dust particles have at least a few small (< 100 nm) particles of black carbon (soot) attached to them. A significant fraction of mineral dust particles are aggregated with soot particles larger than 100 nm. There are many forms of soot present in the samples. The mixing of soot with other aerosols in hot exhaust gases in the highly turbulent freeway environment may be responsible for the Black Carbon/soil-dust aggregation. The simple aggregation of dust particles is common in Arizona soils.

Objective 5: *To determine the size distribution of re-entrained dust and, if reduced from other ambient dust, the mechanism responsible.* The re-entrained dust is smaller in size than that in ambient aerosol arriving at the roadway. The most likely mechanism is disaggregation of larger soil dust particles. Re-entrained soil dust tends to be smaller than 2 μm and therefore contributes to $PM_{2.5}$ as well as PM_{10}.

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